A *Hubble Space Telescope* Snapshot Survey of Nearby Supernovae [1]

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ABSTRACT

We present photometry of 12 recent supernovae (SNe) recovered in a *Hubble Space Telescope* Snapshot program, and tie the measurements to earlier ground-based observations, in order to study the late-time evolution of the SNe. Many of the ground-based measurements are previously unpublished, and were made primarily with a robotic telescope, the Katzman Automatic Imaging Telescope. Evidence for circumstellar interaction is common among the core-collapse SNe. Late-time decline rates for Type IIn SNe are found to span a wide range, perhaps due to differences in circumstellar interaction. An extreme case, SN IIn 1995N, declined by only 1.2 mag in V over about 4 years following discovery. Template images of some SNe must therefore be obtained many years after the explosion, if contamination from the SN itself is to be minimized. Evidence is found against a previous hypothesis that the Type IIn SN 1997bs was actually a superoutburst of a luminous blue variable star. The peculiar SN Ic 1997ef, a "hypernova," declined very slowly at late times. The decline rate of the SN Ia 2000cx decreased at late times, but this is unlikely to have been caused by a light echo.

Subject headings: supernovae: general – supernovae: individual (SN 1995N, SN 1996cb, SN 1997bs, SN 1997ef, SN 1998S, SN 1999bw, SN 1999eb, SN 1999el, SN 1999gi, SN 1999gq, SN 2000P, SN 2000cx)

1. INTRODUCTION

Supernovae (SNe) represent the final, explosive stage in the evolution of certain varieties of stars (see, e.g., Woosley & Weaver 1986; Arnett et al. 1989; Wheeler & Harkness 1990; Filippenko 1997, for reviews of SN types and explosion mechanisms). They synthesize and expel heavy elements, heat the interstellar medium, trigger vigorous bursts of star formation, create neutron stars and sometimes black holes, and produce energetic cosmic rays. Type Ia SNe (SNe Ia), among the most luminous of SNe, are exceedingly useful cosmological tools and have been used to study the expansion history of the Universe. These studies (Riess et al. 1998, 2001; Perlmutter et al. 1999; see Filippenko 2001 for a recent summary) reveal the surprising result that the expansion of the Universe is currently accelerating, perhaps due to a nonzero cosmological constant. SNe are clearly among the most interesting and important constituents of the Universe and should be vigorously studied.

1.1. Discovery and Monitoring of Nearby Supernovae

Detailed spectral and photometric observations of SNe can be used to study the properties of SNe, compare SNe at different redshifts, and gain insights into the evolutionary paths that lead to these energetic explosions. However, until recently, most relatively nearby SNe were found either sporadically, in images taken for other purposes, or at a considerable time after the explosion. Moreover, systematic follow-up observations were scarce for all but a minor fraction of the SNe. During the past few years, however, the situation has changed dramatically, as robotic (or nearly robotic) telescopes have been dedicated to the search for and follow-up of SNe (Filippenko et al. 2001). The two outstanding examples are the Beijing Astronomical Observatory Supernova Search (BAOSS; Li et al. 1996) with a 0.6-m telescope, and the Lick Observatory Supernova Search (LOSS; Treffers et al. 1997; Li

et al. 2000; Filippenko et al. 2001) with the 0.8-m Katzman Automatic Imaging Telescope (KAIT).

KAIT reaches a limit of ~ 19 mag (4σ) in 25-s unfiltered, unguided exposures, while 5-min guided exposures yield $R \approx 20$ mag. 2500−7000 galaxies (most with $cz \leq 6000$ km s^{-1}) are surveyed during any particular season, with a cycle time of $\sim 3{-}10$ days. The search software automatically subtracts new images from old ones and identifies SN candidates which are subsequently examined by undergraduate research assistants.

LOSS discovered its first SN in 1997 (SN 1997bs; Treffers et al. 1997; Van Dyk et al. 2000), then 20 SNe in 1998, 40 in 1999, 36 in 2000, and 68 in 2001. Together, LOSS and BAOSS have found a total of over 180 SNe in the past 5 years. Recently, LOSS teamed up with Michael Schwartz in Arizona, forming the Lick Observatory and Tenagra Observatory Supernova Search (LOTOSS), allowing more SNe to be discovered and followed.

Since most of the SNe found during these systematic searches are discovered very early in their development, and have a large amount of follow-up time devoted to them, they are among the world's best-studied SNe (see, e.g., Li et al. 2000, 2001a; Leonard et al. 2002a,b). Li, Filippenko, & Riess (2001) and Li et al. (2001b) also show that these surveys are least affected by observational biases, and provide the most accurate luminosity function for SNe. The rate of intrinsically peculiar SNe Ia, for example, is found to be unexpectedly high.

1.2. The Environment and Late-Time Detection of Supernovae

The explosion of a SN leaves few traces of the star that underwent the catastrophic event. An important clue to the nature of the progenitor is its environment (e.g., Boffi 1999). Unfortunately, most studies of the sites of SNe have been hampered by the limited

spatial resolution of ground-based observations (e.g., van den Bergh 1988; Panagia & Laidler 1991; Boffi, Sparks, & Macchetto 1999). This problem can be partially overcome by using *Hubble Space Telescope (HST)* archival images (e.g., Van Dyk et al. 1999a,b, 2000). However, although the chance that the site of any particular SN has been imaged by *HST* during other programs is rapidly growing, it is still relatively low. Also, some of the positions of older SNe (prior to 1990) were uncertain, compromising studies of their local environment.

To remedy this, an *HST* Snapshot survey program (GO-8602) of recent, nearby SNe was conducted starting in Cycle 9, requesting WFPC2 images of the sites of 23 LOSS and BAOSS SNe[7] with $cz \leq 6000$ km s^{-1}. These SNe provide the best spatial resolution and have accurate positions (often better than $\pm 0\farcs5$). In addition, they were generally discovered early in their development, and had extensive ground-based follow-up studies. 45 out of the 70 ($\sim 45\%$) requested observations have been made, with 20 out of the 23 SNe ($\sim 90\%$) observed at least once and 13 ($\sim 56\%$) of the SNe having images in more than one filter; thus, the chances of imaging the sites of specific SNe are much higher than by using the archive alone. Moreover, the data are all obtained in a uniform way using the same set of filters.

One advantage of concentrating the Snapshot survey on very recent, nearby, well-studied SNe is that many of the SNe themselves are still visible in the *HST* images, providing late-time photometry superior to that achieved from the ground; at such late times, the SNe are so faint that their ground-based photometry is contaminated by neighboring stars within the seeing disk. Late-time photometry, especially through more than one filter, provides not only useful information on the underlying physics for the lingering light, such

[7]Some of these 23 SNe were first discovered by other groups, but subsequently found in the course of LOSS and BAOSS.

as radioactive decay of long-lived isotopes, interaction with circumstellar matter, and light echoes, but also the relative brightness of SNe still present in "template" images taken at various epochs compared to their maximum light. To obtain proper photometry of a SN, which often occurs in a complicated background (e.g., spiral arms or H II regions), observers are required to take template images of the host galaxy a year or two after the discovery, and then do image subtraction. It is often assumed that the light of the SN is essentially negligible in these template images, but as we later discuss in this paper, some SNe (especially those of Type II) are quite long-lived and may contaminate the template images.

Detailed analysis of the SN environments is still underway, and the results will be discussed elsewhere. In this paper, we report on SNe recovered in the Snapshot images. Section 2 contains a description of the observations and analysis of the photometry, while § 3 presents the light curves of all recovered SNe, details of individual SNe, and comparison of late-time light-curve shapes and decline rates. Our conclusions are summarized in § 4.

2. OBSERVATIONS AND REDUCTIONS

Table 1 lists the observational details of all 12 SNe recovered in the Snapshot program GO-8602, while Figure 1 shows the finding charts for the SNe. All the Snapshot images were obtained in pairs to facilitate removal of cosmic rays.

To properly identify the SNe in the WFPC2 images, we have used the best available astrometry in the literature (details of the sources for astrometry can be found in § 3), and derived the position of the SNe using the pointing information in the image headers. In most cases, each of the SNe identified in Figure 1 is the only object within a $0''.5$ radius error circle. Three exceptions are SNe 1997bs, 1999gi, and 1999gq. Identification of SN

1997bs in the Snapshot images was accomplished by comparing them to the finder chart in Van Dyk et al. (2000), where SN 1997bs was apparent in a co-added deep *HST* archival WFPC2 F555W image. SN 1997bs is only marginally detected in our F555W image taken on 2001 March 4 UT (UT dates are used throughout this paper), and not detected in the two F814W images (see details in § 3). Three stars are within the $0\farcs5$ radius error circle of SN 1999gi; following Smartt et al. (2001), we identify the brightest object as the SN. No object is within the $0\farcs5$ radius error circle of the position of SN 1999gq. However, our estimate for the brightness of SN 1999gq (by comparison with the light curve of the SN II-P 1988A; Turatto et al. 1993) is 22.0 ± 0.3 mag at the time of the Snapshot observation, so the SN should be visible in the image. Fortunately, we have several excellent KAIT images of SN 1999gq, and after rotating one of them to the orientation of the WFPC2 image, we measured the relative angular distance between the SN and several bright stars from the KAIT image, and identified the SN using the corresponding offsets from these bright stars seen in the WFPC2 four-chip mosaic. We find that the pointing for the Snapshot observations of SN 1999gq is off by more than $6\farcs0$, relative to information in the data header.

To measure SN magnitudes in the Snapshot images, we have used the "HSTphot" package developed by Dolphin (2000a). The data quality images are used to mask bad pixels and defects in the data image using the program *mask*. The program *crmask* is used to remove cosmic rays, and the program *coadd* is used to combine the two images. The program *getsky* is then used to determine the sky value at each pixel. Hot pixels are identified and masked using the program *hotpixels*. Following all this preprocessing, the images are fed into the program *hstphot*, where the magnitudes in the WFPC2 system are measured for all the stars using the zero points and charge-transfer efficiency (CTE) determined by Dolphin (2000b). We have used option flag 10 for *hstphot*, which is a combination of turning on local sky determination and turning off aperture corrections.

Turning on local sky determination is recommended by the HSTphot manual[8], while turning off aperture corrections is necessary because for most of the Snapshot images, there are not enough bright and isolated stars to determine a reliable aperture correction. Default aperture corrections are applied to the photometry obtained with the *HST* filters; these are probably accurate, in general, to 0.02 mag in F555W and F814W, and to 0.05 mag in F675W (cf. the HSTphot manual). These uncertainties are combined in quadrature with the photometric uncertainties returned by *hstphot*, and the resulting uncertainties are reported in the last column of Table 1.

Ideally, to tie the magnitudes in the WFPC2 system (Table 1) to the early-time light curves of the SNe obtained from the ground [which are typically in the standard Johnson (UBV) and Cousins (RI) system], a magnitude transformation such as those described by Holtzman et al. (1995) and Dolphin (2000b) should be applied. (Note, however, that although these transformations are generally applicable to stars, they might not be as applicable to emission-line dominated sources, such as SNe.) We have done this for SN 2000cx (see discussion below), but not for the other SNe because of the difficulty of getting late-time color information for them. The differences in these two magnitude systems can be estimated using the procedure described by Dolphin (2000b) [his equation (1) and Tables 6 and 7]:

$$V - F555W = -0.052(V - I) + 0.027(V - I)^2,$$

$$I - F814W = -0.062(V - I) + 0.025(V - I)^2,$$

where V and I are the magnitudes in the standard ground-based system, and $F555W$ and $F814W$ are the magnitudes in the WFPC2 system. A reasonable range for the late-time

[8]See URL http://www.noao.edu/staff/dolphin/hstphot/

$V - I$ color of the SNe is -0.5 to 2 mag, which indicates that the differences between V and $F555W$, as well as between I and $F814W$, are smaller than 0.04 mag. In subsequent discussions, we will neglect the difference between these two systems.

For SN 2000cx, since the F675W and F814W observations were taken at the same time, we can use the following equations (also from Dolphin 2000b) to transform the magnitudes:

$$R - F675W = +0.273(R - I) - 0.066(R - I)^2,$$

$$I - F814W = -0.112(R - I) + 0.084(R - I)^2.$$

The $(R - I)$ color should have minimal difference from its WFPC2 system equivalent $(F675W - F814W)$, which is 0.55 mag from Table 1. When this color is applied to the above equations, we get $R = 22.10 \pm 0.06$ and $I = 21.38 \pm 0.04$, which are the magnitudes for the SN 2000cx Snapshot observations used in subsequent discussions.

3. RESULTS

Figures 2 – 5 show the light curves of the 12 SNe recovered in the Snapshot observations. The solid circles are the photometry from *HST*, while the open circles represent ground-based measurements. As discussed above, the F555W and V-band magnitudes are plotted together, as are F814W with the I band. The sources of the ground-based photometry are listed below in the notes on individual SNe.

3.1. SN 1995N

SN 1995N in MCG $-02-38-017$ (also Arp 261) was discovered by Pollas (1995) on 1995 May 5. Optical spectra of the object obtained by Benetti, Bouchet, & Schwarz (1995)

and by Garnavich & Challis (1995) showed it to be a Type IIn SN; specifically, it resembles SN 1988Z in its characteristics (see Filippenko 1997 for a summary of SNe IIn). Van Dyk et al. (1996a) reported the detection of radio emission from the SN at 3.6 cm on 1995 June 16 and also provided a precise position of the SN at $\alpha = 14^h49^m28^s.313$, $\delta = -10^\circ10'13''.92$ (equinox J2000.0), which are the coordinates we used to locate the SN in the Snapshot observations.

The ground-based photometry (open circles in Figure 2) consists of previously unpublished observations taken at the 1.0-m Nickel telescope at Lick Observatory except the two latest V-band points, which were obtained from Schaefer & Roscherr (1999) and Schaefer (2001). In particular, the Schaefer (2001) observations (which yielded $V = 21.1 \pm 0.3$ mag) with the McDonald Observatory 2.1-m telescope were made on the same UT date as our *HST* Snapshot observation (which yielded $F555W = 21.213 \pm 0.023$), and the reported magnitudes agree with each other very well. The earliest Nickel observations taken on 1995 May 23 (18 days after discovery) yielded a V mag of 18.72, about 1.2 mag fainter than the reported brightness at the time of discovery (Pollas 1995). We suspect that the discovery magnitude is erroneous; Fransson et al. (2002) argue that the SN was already about 10 months old at the time of discovery, and it declined only by another 1.2 mag in $\sim$ 1400 days after the first Nickel observation.

As noted by Schaefer & Roscherr (1999) and Schaefer (2001), SN 1995N has a very slow optical decline rate, only 2.5 mag (3 from the Nickel photometry) in the V band over $\sim$2200 days after discovery. This is consistent with the slow spectral evolution reported by Fransson et al. (2002). The decline rate for the V band increased from $(0.08 \pm 0.01$ mag)/(100 days) (from discovery to about 1400 days after discovery) to $(0.18 \pm 0.01$ mag)/(100 days) (from about 1400 days to 2200 days after discovery), while the decline rate for the I band decreased from $(0.13 \pm 0.01$ mag)/(100 days) (from discovery to about

1900 days after discovery) to $(0.05 \pm 0.01$ mag$)/(100$ days) (from about 1900 to 2200 days after discovery). Although the decline rates in the two passbands seem to change in opposite directions, the light curves are not sufficiently well sampled to make any definitive conclusions.

Roscherr & Schaefer (2000) investigated the light echoes from dust formed in the circumstellar wind of SNe IIn, and concluded that they cannot properly account for the slow decline seen in SNe IIn 1988Z and 1997ab. They suggested that the shock interaction of the SN ejecta colliding with the circumstellar wind is the dominant source of late-time emission of these two SNe IIn, consistent with previous suggestions (e.g., Filippenko 1997; Aretxaga et al. 1999). As we discuss in subsequent sections, the late-time decline rates for SNe IIn span a wide range, so there may be differences in the degree of circumstellar interaction among these SNe.

Fransson et al. (2002) investigated the late-time spectral evolution of SN 1995N from both ground-based and *HST* observations, and concluded that the late-time emission of SN 1995N is most likely powered by X-rays from the interaction of the ejecta and the circumstellar medium of the progenitor. They proposed that the progenitors of SNe IIn are similar to red supergiants in their superwind phases, when most of the hydrogen-rich gas is expelled in the last $\sim 10^4$ years before explosion.

3.2. SN 1996cb

SN 1996cb in NGC 3510 was first discovered by M. Aoki (Nakano & Aoki 1996) on 1996 December 15, and then independently by BAOSS (Qiao et al. 1996) on 1996 December 18. Garnavich, Kirshner, & Berlind (1996a) classified SN 1996cb as a SN II near maximum brightness from a spectrum obtained 2 days after discovery; using a spectrum obtained 16

days later, however, they suggested that it was a Type IIb SN (Garnavich et al. 1996b), similar to SN 1993J (e.g., Filippenko, Matheson, & Ho 1993). An early radio detection was reported by Van Dyk et al. (1996b), who also provided a precise position for SN 1996cb as $\alpha = 11^h3^m42^s.00$, $\delta = +28°54'14''.2$ (equinox J2000.0).

Qiu et al. (1999) reported early spectroscopic and photometric (BVR) observations of SN 1996cb, and concluded that although SN 1996cb is indeed a SN IIb similar to SN 1993J, the two SNe have some differences in both the photometric and spectral evolution. Compared to SN 1993J, SN 1996cb shows broader light curves, as well as earlier and stronger He I emission; thus, SN 1996cb may have thicker hydrogen and helium layers than SN 1993J in the outer ejecta.

The early V-band photometry in Figure 2 is taken from Qiu et al. (1999). There is no I-band photometry for SN 1996cb available in the literature, and the point shown in Figure 2 is obtained by assuming SN 1996cb has the same $V-I$ color at the second peak as SN 1993J (Richmond et al. 1996). No reliable late-time decline rate can be obtained for SN 1996cb, since there is a 1400 day gap between the two latest V-band observations, and there is only a 13-day difference between the two F814W *HST* Snapshot observations. However, it can be inferred from the latest point in the V band light curve that the decline rate of SN 1996cb does become significantly slower at late times, probably caused by the interaction between the SN ejecta and the circumstellar medium. Evidence of circumstellar interaction is also found in the case of SN 1993J, the prototypical SN IIb (Filippenko, Matheson, & Barth 1994; Matheson et al. 2000).

3.3. SN 1997bs

SN 1997bs in NGC 3627 was discovered by LOSS (Treffers et al. 1997) on 1997 April 15, the first LOSS SN discovery. A spectrum obtained by Filippenko, Barth, & Gilbert (1997) showed that the SN is a peculiar SN IIn. A precise position of the SN was provided by Cavagna & Manca (1997) as $\alpha = 11^h20^m14^s.25$, $\delta = +12°58'19''.6$ (equinox J2000.0).

Van Dyk et al. (2000) reported early photometry of SN 1997bs from both KAIT and archival *HST* WFPC2 observations, some of which are shown in Figure 2. Based on these observations, Van Dyk et al. questioned the identification of SN 1997bs as a bona fide SN, and suggested that it is more likely to be a "superoutburst" of a luminous blue variable star, analogous to η Carinae, and similar to SN 1961V in NGC 1058 (Goodrich et al. 1989; Filippenko et al. 1995) and SN 1954J in NGC 2403 (Smith, Humphreys, & Gehrz 2001). More recent examples of SN 1997bs-like objects include SN 1999bw (Filippenko, Li, & Modjaz 1999; see discussion below), SN 2000ch (Filippenko 2000a; Wagner et al. 2000), and SN 2001ac (Matheson & Calkins 2001). Van Dyk et al. (2000) suspected that the progenitor of SN 1997bs might have survived the outburst, since the SN was seen in early-1998 *HST* images at $F555W = 23.4$ mag, about 0.5 mag fainter than the progenitor identified by Van Dyk et al. (1999b) in a prediscovery image.

The Snapshot observations seem to provide evidence against the superoutburst interpretation of SN 1997bs. SN 1997bs is marginally detected in the F555W image taken on 2001 March 4 ($F555W = 25.8 \pm 0.3$ mag), and not detected in the two F814W images taken on 2001 February 24 and May 28 (limiting magnitude about 25.0). These observations show that SN 1997bs continued to decline after early 1998, at 0.21 mag/(100 days) in the V band, and > 0.41 mag/(100 days) in the I band, inconsistent with the suggestion that the progenitor of the SN survived the explosion. While formation of dust in the ejecta could explain the continuous decline in the optical wavelengths (V and I), it is inconsistent

with the color evolution. The SN should become progressively redder if dust is forming in the ejecta, but SN 1997bs has become progressively bluer, from $V - I = 3.0$ mag in early 1998 to $V - I < 0.8$ mag in early 2001. Additional deep multiband *HST* images of SN 1997bs could provide useful information on the late-time behavior of the object and help to constrain its nature.

3.4. SN 1997ef

SN 1997ef in UGC 4107 was discovered by Y. Sano (Nakano & Sano 1997) on 1997 November 25. Garnavich et al. (1997a) obtained a spectrum of the object that showed very unusual broad features, and failed to identify it as any known type of SN. Filippenko & Martin (1997) suggested that the object may be a previously unobserved, extreme example of a stripped (Type Ic-like) SN; this was also proposed by Garnavich et al. (1997b) and by Wang, Howell, & Wheeler (1998). A precise position of the SN was provided by Nakano & Sano (1997): $\alpha = 7^h57^m2^s.82$, $\delta = +49°33'40''.2$ (equinox J2000.0).

SN 1997ef is the subject of a number of studies, because of its peculiar spectroscopic behavior and its possible association with a gamma-ray burst that occurred on 1997 November 15 (e.g., Wang & Wheeler 1998; Nomoto et al. 1999; Iwamoto et al. 2000; Mazalli, Iwamoto, & Nomoto 2000). Iwamoto et al. (2000) also claim that SN 1997ef belongs to a class of objects termed "hypernova," the prototype of which is SN 1998bw (e.g., Iwamoto et al. 1998; Woosley, Eastman, & Schmidt 1999).

The early I-band photometry of SN 1997ef shown in Figure 3 consists of previously unpublished KAIT observations. These data show that SN 1997ef declined at a rate of 1.27 mag/(100 days) in the first 100 days after discovery. The decline rate changed dramatically thereafter, and the SN faded only 2.5 mag over the next 1100 days. Again, circumstellar

interaction or a light echo could be a possible cause.

3.5. SN 1998S

SN 1998S in NGC 3877 was discovered by BAOSS on 1998 March 3 (Li & Li 1998). A spectrum taken by Filippenko & Moran (1998) indicated that SN 1998S was a peculiar SN IIn. Van Dyk et al. (1999c) reported radio detection of SN 1998S on 1999 October 28, and provided a precise position as $\alpha = 11^h46^m6^s.140$, $\delta = +47°28'55''.45$ (equinox J2000.0).

The early-time photometry of SN 1998S shown in Figure 3 consists of KAIT observations taken from Modjaz et al. (2002, in preparation). Early optical and infrared photometry of SN 1998S was also reported by Fassia et al. (2000) and Liu et al. (2000). The V-band and I-band decline rates for SN 1998S seem to exhibit two significant changes, the first at $\sim$100 days after maximum brightness, and the second roughly 300 days after maximum. The late-time (> 300 d) decline rate of SN 1998S is (0.34 ± 0.03 mag)/(100 days) in the V band, and (0.56 ± 0.05 mag)/(100 days) in the I band. This slow decline rate is certainly caused by strong circumstellar interaction, as discussed by Leonard et al. (2000) based on spectropolarimetry and spectroscopy of SN 1998S, as well as from its radio and X-ray emission (Pooley et al. 2002).

3.6. SN 1999bw

SN 1999bw in NGC 3198 was discovered by LOSS (Li 1999). A precise position was also provided by Li (1999) as $\alpha = 10^h19^m46^s.81$, $\delta = +45°31'35''.0$ (equinox J2000.0). Spectra taken by Garnavich et al. (1999a) and Filippenko et al. (1999) showed barely resolved hydrogen Balmer emission lines, and Filippenko, Li, & Modjaz (1999) classified the object as a SN 1997bs-like Type IIn SN.

The early-time photometry of SN 1999bw shown in Figure 3 consists of previously unpublished KAIT observations. SN 1999bw declined 5.6 mag in the first 620 days after maximum, while SN 1997bs declined about 7.0 mag in the same period (estimated from Figure 2), so their photometric evolution seems to differ to some extent, even though they have similar spectra and low peak luminosity (Filippenko, Li, & Modjaz 1999).

3.7. SN 1999eb

SN 1999eb in NGC 664 was discovered by LOSS (Modjaz & Li 1999) on 1999 October 2. The SN was also present in earlier LOSS images taken on 1999 September 22 and 29. A precise position is reported by Modjaz & Li (1999) as $\alpha = 1^h43^m45^s.45$, $\delta = +4^\circ13'25''.9$ (equinox J2000.0). Garnavich et al. (1999b) obtained a spectrum of the SN and classified it as a Type IIn. Terlevich, Fabian, & Turatto (1999) suggested that SN 1999eb was possibly associated with a gamma-ray burst that occurred on 1999 October 2. However, as pointed out by Filippenko (2000b), this association seems quite unlikely, given the fact that SN 1999eb was present in LOSS images on 1999 September 22, 10 days before the gamma-ray burst.

The early-time photometry of SN 1999eb shown in Figure 4 consists of KAIT data taken from Modjaz et al. (2002, in preparation). The F555W observation $\sim$450 days after maximum brightness is in good agreement with a linear extrapolation from early points, suggesting that the decline rate in the V band probably does not change significantly during this period. There are three $F814$ observations for SN 1999eb, which yield a good estimate of the late-time decline rate as $(0.86 \pm 0.01$ mag$)/(100$ days$)$.

3.8. SN 1999el

SN 1999el in NGC 6951 was discovered by BAOSS (Cao et al. 1999) on 1999 October 20. A precise position was also provided by Cao et al. (1999) as $\alpha = 20^h37^m17^s.83$, $\delta = +66°6'11''.5$ (equinox J2000.0). From a spectrum taken with the BAO 2.16-m telescope, Filippenko (1999) identified SN 1999el as a very early Type IIn SN.

The early-time photometry of SN 1999el shown in Figure 4 consists of KAIT data taken from Modjaz et al. (2002, in preparation). The late-time Snapshot observations suggest that the decline rate of SN 1999el in both the V and I bands has changed at late times. The two F814W Snapshot observations yield a late-time I-band decline rate of $(1.30 \pm 0.03$ mag)/(100 days).

3.9. SN 1999gi

SN 1999gi in NGC 3184 was discovered by R. Kushida (Nakano & Kushida 1999) on 1999 December 9. A precise position is also reported by Nakano & Kushida (1999) as $\alpha = 10^h18^m16^s.66$, $\delta = +41°26'28''.2$ (equinox J2000.0). Jha et al. (1999a) obtained a spectrum of SN 1999gi and classified it as a SN II.

The well-sampled early-time light curves for SN 1999gi shown in Figure 4 are the KAIT observations taken from Leonard et al. (2002b), and indicate that SN 1999gi is a normal Type II-P SN. The F555W observation is consistent with a linear extrapolation of the latest KAIT data, and yields a decline rate of $(1.01 \pm 0.01$ mag)/(100 days).

Our Snapshot image of SN 1999gi was used by Smartt et al. (2001) to place an upper limit on the mass of the progenitor of the SN. However, as discussed more fully by Leonard et al. (2002b), their derived upper limit may be too stringent, since the distance they used to the SN (7.9 Mpc) is substantially less than the distance derived through the expanding

photosphere method (~ 12 Mpc) and other recent distance estimates to the host galaxy.

3.10. SN 1999gq

SN 1999gq in NGC 4523 was discovered by LOSS (Papenkova & Li 1999) on 1999 December 23. An independent discovery was reported by Armstrong (1999). SN 1999gq was classified as a SN II from spectroscopic observations by Ayani & Yamaoka (1999) and by Jha et al. (1999b). A precise position of the SN was reported by Papenkova & Li (1999) as $\alpha = 12^h33^m48^s.32$, $\delta = +15°10'48''.2$ (equinox J2000.0).

The sparse early-time photometry of SN 1999gq shown in Figure 5 consists of previously unpublished KAIT observations. The SN has not been well observed, and the gap between the early-time and Snapshot observations is too large (> 500 days) to determine a reliable decline rate.

3.11. SN 2000P

SN 2000P in NGC 4965 was discovered by R. Chassagne (Colas & Chassagne 2000) on 2000 March 8. A precise position of the SN is reported by Colas & Chassagne (2000) as $\alpha = 13^h7^m10^s.53$, $\delta = -28°14'2''.5$ (equinox J2000.0). SN 2000P was spectroscopically classified as a SN IIn (Cappellaro et al. 2000; Jha et al. 2000).

The early-time photometry of SN 2000P shown in Figure 5 consists of previously unpublished KAIT observations. The F555W observation 250 days after discovery indicates that the decline rate of SN 2000P changed at late times.

3.12. SN 2000cx

SN 2000cx in NGC 524 was discovered by LOSS (Yu, Modjaz, & Li 2000) on 2000 July 17. Yu et al. also provided a precise position of the SN as $\alpha = 1^h24^m46^s.15$, $\delta = +09°30'30''.9$ (equinox J2000.0). SN 2000cx was classified as a SN 1991T-like peculiar SN Ia from a spectrum obtained by Chornock et al. (2000).

SN 2000cx is one of the best-monitored SNe Ia in the literature. The early spectroscopic and photometric observations were reported by Li et al. (2001a), which showed SN 2000cx to be a unique SN Ia. SN 2000cx showed an apparent asymmetry in the B-band light curve, in which the premaximum brightening is relatively fast (similar to that of the normal SN 1994D), but the postmaximum decline is relatively slow (similar to that of the overluminous SN 1991T). The color of SN 2000cx is also extremely blue. The premaximum spectra of SN 2000cx are similar to those of SN 1991T-like objects, but its overall spectral evolution is quite different, with strong Si II lines until three weeks past B maximum and a slow change in the excitation stages of iron-peak elements. Matter is also moving at high expansion velocities in the ejecta of SN 2000cx. Based on these observations, Li et al. proposed that SN 2000cx may be an overluminous object like SN 1991T, but with a larger yield of ^{56}Ni and a higher kinetic energy in the ejecta.

The early-time photometry of SN 2000cx in Figure 5 consists of the KAIT observations from Li et al. (2001a). The Snapshot observations of SN 2000cx were made about a year after discovery, which show that the decline rate of the SN in both the R and I bands has decreased at late times. The decline rate measured from the latest KAIT points and the Snapshot observations is $(1.61 \pm 0.05$ mag)/(100 days) for the R band, and $(1.10 \pm 0.08$ mag)/(100 days) for the I band. The change of decline rate at late times for SN 2000cx is most likely not due to light echoes, since SN 2000cx occurred at the outskirts of an early-type (S0) galaxy, where a dusty environment is not expected. Light echoes have

been successfully detected around at least two SNe Ia: SN 1991T, after 600 days following maximum (Schmidt et al. 1994), and SN 1998bu, after 500 days following maximum (Cappellaro et al. 2001).

3.13. Comparison of SNe IIn

Seven of the 12 SNe recovered in our Snapshot program are SNe IIn and show slow evolution at late times. As discussed in previous sections, some differences among their late-time decline rates are found. This is to be expected because the subclass of SNe IIn is known to span a very broad range of properties (e.g., Filippenko 1997; Filippenko, Li, & Modjaz 1999). Some SNe IIn are subluminous (e.g., SN 1997bs with $M_V = -13.8$ mag, Van Dyk et al. 2000), others are moderately bright (e.g., SN 1999eb with $M_V = -18.6$ mag, assuming $H_0 = 65$ km s^{-1} Mpc^{-1}), while a few can rival the brightness of a SN Ia (e.g., SN 1998S with $M_V = -19.6$ mag, Leonard et al. 2000).

Figure 6 shows the light curves of all the SNe IIn recovered in our Snapshot program. Even though the data are often limited by a large gap in time between the ground-based and the *HST* Snapshot photometry, or by large time intervals between the Snapshot observations, it is still easily seen from Figure 6 that the light-curve shapes for the SNe IIn are quite different: some decline monotonically after maximum (e.g., SN 1999eb in the V band, and SN 1999eb in the I band), while others experience multiple changes in their decline rate (e.g., SNe 1997bs and 1998S in the V band). There is no clear correlation between the light-curve shapes and the luminosities of the SNe IIn: the overluminous SN 1998S and the subluminous SN 1997bs have similar narrow peaks, while the moderately bright SN 1999eb has a very broad peak.

Table 2 lists the late-time decline rates for some of the SNe IIn, and it is clear that

they span quite a large range. Note, however, that these are sometimes derived at different evolutionary phases of the SNe, so a close comparison should not be made.

We suspect that the different light-curve shapes of SNe IIn are closely related to their progenitor properties. Relevant factors may be the density, structure, and radial distance of the circumstellar medium, the mass and composition of the progenitor, and so forth.

3.14. Contamination of SN Light in Template Images

The two vertical dotted lines in Figure 6 mark one and two years after maximum light. It can be seen that the SNe declined 0.3 to 7.3 mag in the V band, and 0.3 to 6.2 mag in the I band at one year after discovery, while they declined 0.6 to 8.5 mag in the V band, and 0.8 to 8.3 mag in the I band at two years after discovery. These numbers indicate that the template images for these SNe IIn taken at one and two years after discovery will have different degrees of contamination from the SN light. For the extreme case of SN 1995N, which had declined only 0.6 mag in the V band and 0.8 mag in the I band by two years after discovery, the template images are seriously contaminated by the SN. While SN 1995N is at a fortunate location without a complicated background and the point-spread-function technique used to derive the photometry reported in § 3.1 is adequate, other SNe having similar behavior may not be so fortunate and it will take a very long time to obtain template images without significant contamination from the SN light. On the other hand, SN 1998S declined 7.3 mag in the V band and 6.2 mag in the I band by one year after discovery, which means the SN was only 0.30% and 0.33% of the peak V and I-band brightness, respectively; thus, the images taken one year after discovery will be good templates for those taken around maximum light.

We have well-defined late-time light curves for a few other SNe in our sample. For SN

Ia 2000cx, we measured a decline of 9.0 mag in the R band and 8.1 mag in the I band by one year after discovery, which indicates that the late-time templates are not seriously contaminated by the SN light. For SN II-P 1999gi, we measured a decline of 4.6 mag in the V band by one year after discovery, when the SN was about 1.5% of its peak brightness. High-precision photometry of SNe II-P thus requires the template images to be taken at a time considerably later than one year after discovery.

4. CONCLUSIONS

In this paper we present 12 SNe recovered in the *HST* Cycle 9 Snapshot program GO-8602. *HST* photometry was obtained for the SNe, and the data were tied to early-time ground-based observations, in order to study the late-time evolution of various types of SNe. Much of the ground-based data presented here are previously unpublished, and were obtained primarily with the Katzman Automatic Imaging Telescope.

The successful detection of SN 1996cb, a SN IIb, more than 4 years after discovery suggests the existence of interaction between the SN ejecta and the circumstellar medium. The peculiar SN Ic 1997ef, a "hypernova," is found to decline slowly between 100 and 1200 days after discovery. Two bright SN II-P discovered in 1999, SNe 1999gi and 1999gq, are also both recovered in the Snapshot observations.

We find that there is a diversity in the late-time evolution of SNe IIn, perhaps due to differences in circumstellar interaction. Some decline monotonically, such as SN 1999eb within the first 660 days following maximum brightness. Others experience multiple changes in their decline rate, such as SNe 1998S, 1999el, and 2000P. SN 1995N fades very slowly, declining by only 1.2 mag in V over ~ 1400 days following discovery. Thus, template images of some SNe must be obtained many years after the explosion, to minimize contamination

from the SN itself.

SN 1997bs, a subluminous SN IIn that was suggested by Van Dyk et al.(2000) to be a superoutburst of a massive luminous blue variable, is only marginally detected in the F555W observations and not at all in the two F814W images, casting some doubt on the hypothesis that the progenitor survived the explosion. SN 1999bw, an object similar to SN 1997bs in terms of its spectrum and peak luminosity, showed a slower late-time decline rate than SN 1997bs.

SN 2000cx is the only SN Ia recovered in the Snapshot observations. Both the R-band and I-band decline rates are found to decrease at late times, but we do not believe this is due to a light echo.

Circumstellar interaction is apparently very common in the late-time evolution of core-collapse SNe, such as SNe IIn, SNe IIb, and possibly some SNe II-P and SNe Ic.

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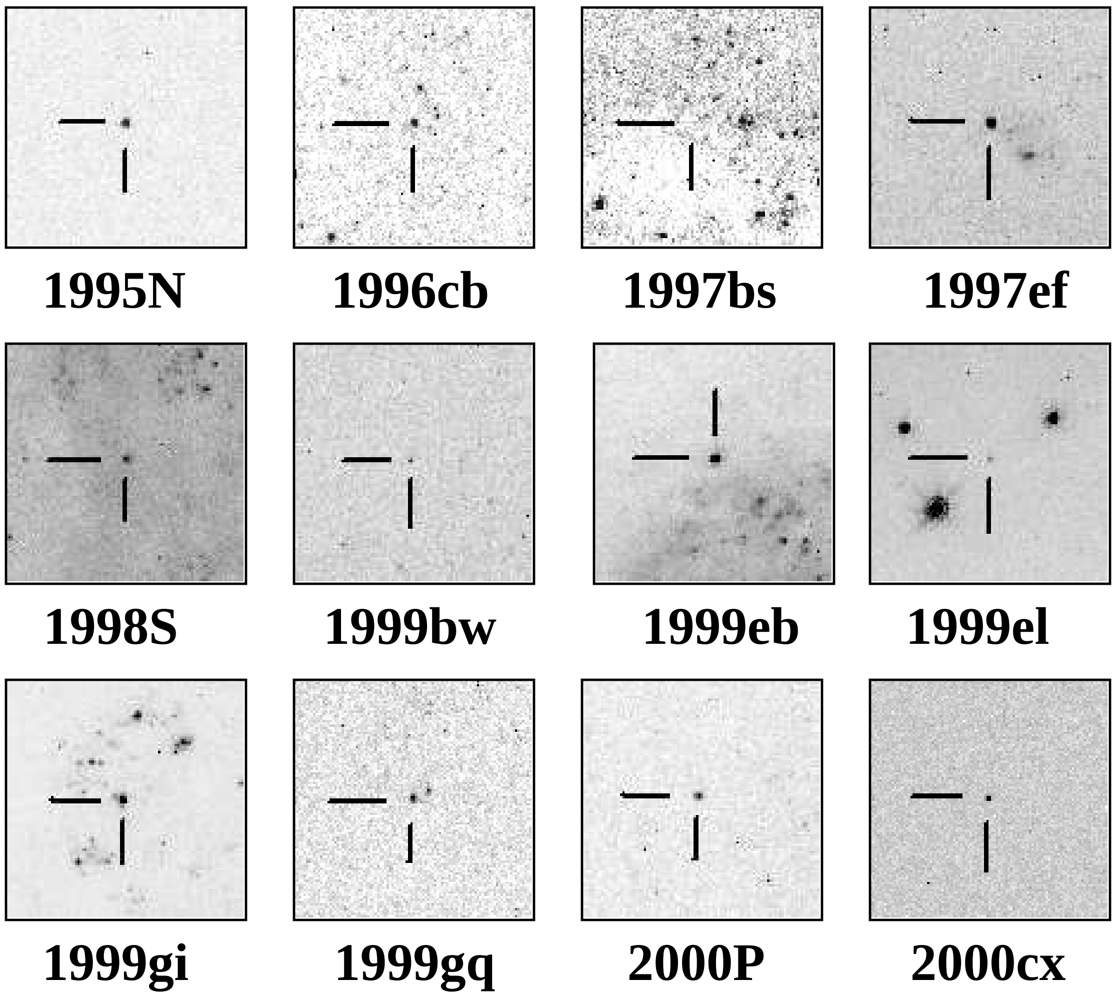

Fig. 1.— Finder charts for the 12 SNe recovered in the Snapshot observations. Each panel consists of 156×156 PC pixels, and is $7\farcs2 \times 7\farcs2$ in size.

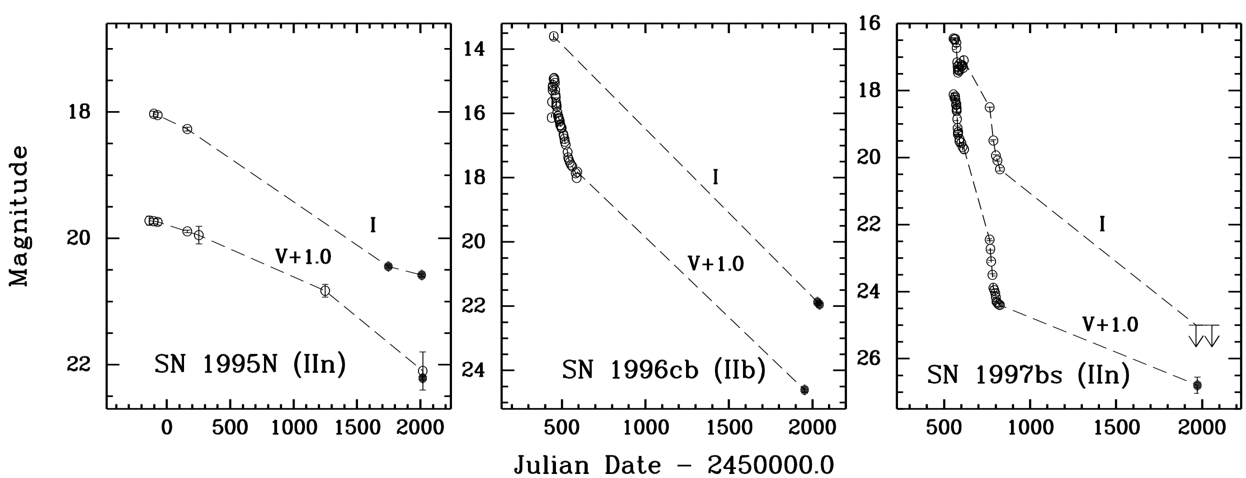

Fig. 2.— The light curves of SNe 1995N, 1996cb, and 1997bs. The open circles are the photometry from ground-based observations (see text for sources), and the solid circles are data obtained from the *HST* Snapshot observations. An offset has been added to the V-band data for clarity. Dashed lines between widely separated points are drawn to help guide the eye; they represent only the average decline rates, not the detailed light curves.

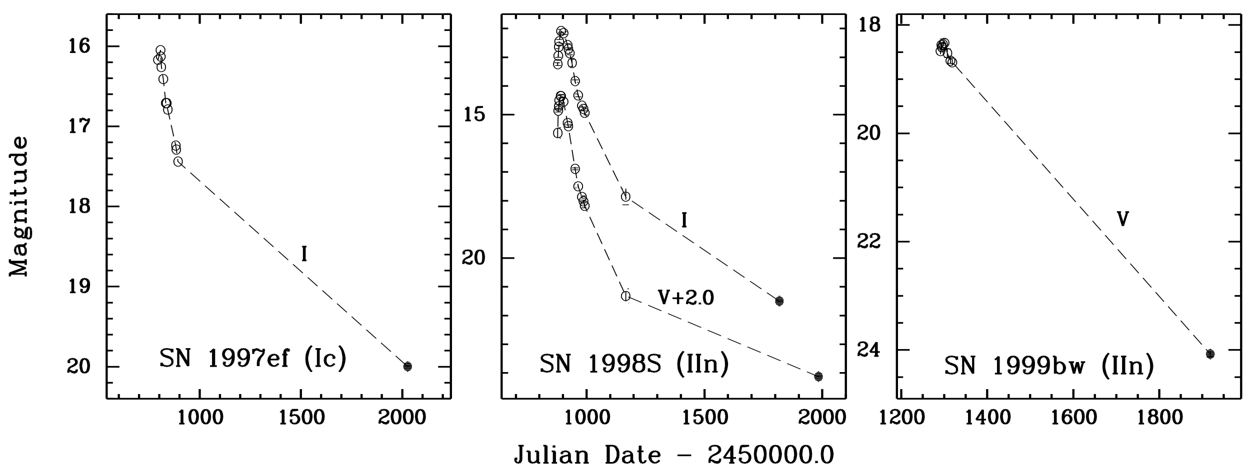

Fig. 3.— The same as Figure 2, but for SNe 1997ef, 1998S, and 1999bw.

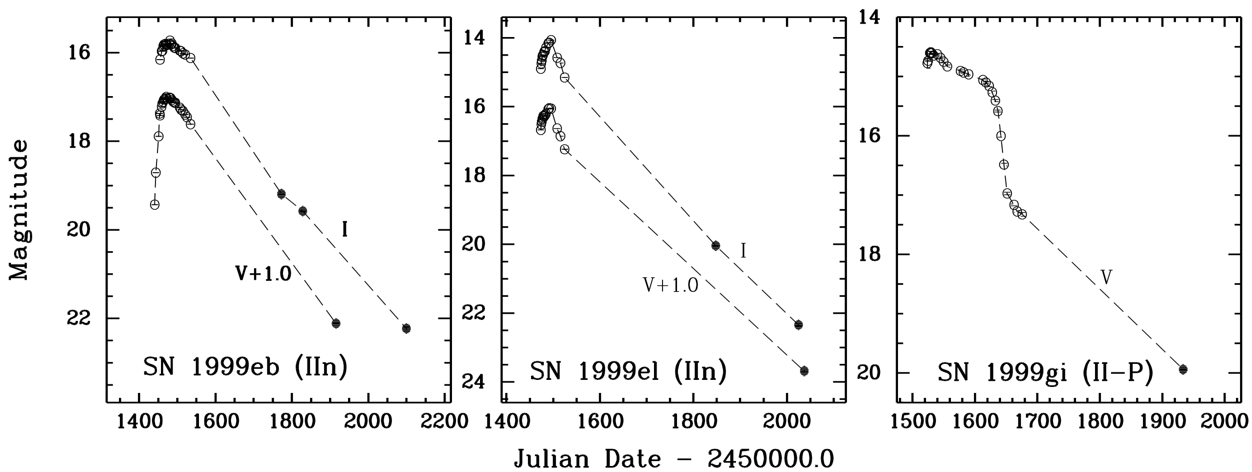

Fig. 4.— The same as Figure 2, but for SNe 1999eb, 1999el, and 1999gi.

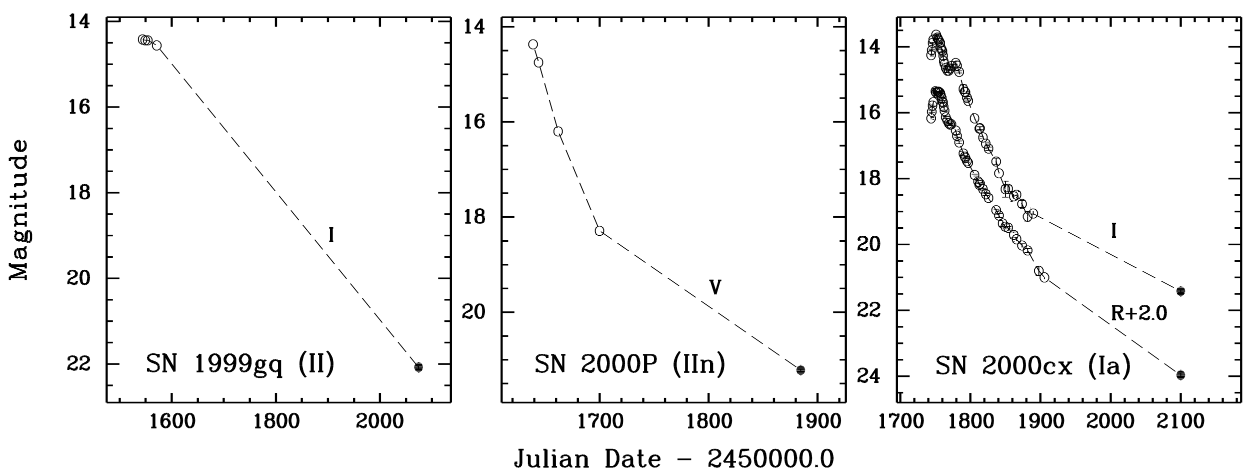

Fig. 5.— The same as Figure 2, but for SNe 1999gq, 2000P, and 2000cx.

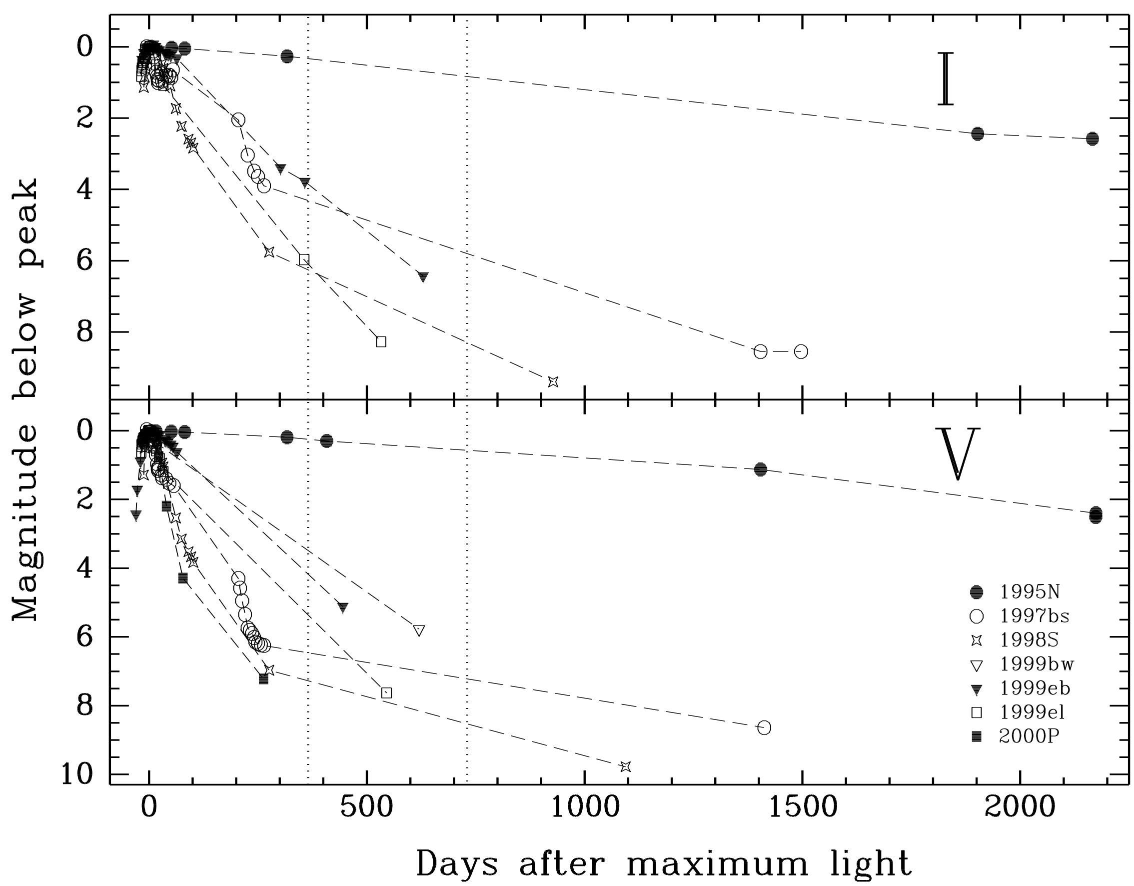

Fig. 6.— Comparison of the light curves of SNe IIn recovered in the Snapshot observations. The light curves have been shifted to match the time of maximum light and the peak brightness. The two vertical dotted lines indicate one and two years after maximum brightness. One can see the large variety of photometric evolution among SNe IIn.

Table 1. Observational details of the Snapshot SNe

SN	Type	Date[a]	Age[b]	Filter	Exp[c]	J.D.[d]	Magnitude[e]
1995N	IIn	Jul 22, 2000	1903	F814W	700	51747.44	20.45±0.02
1995N	IIn	Apr 11, 2001	2166	F814W	700	52010.88	20.58±0.02
1995N	IIn	Apr 19, 2001	2174	F555W	700	52018.45	21.21±0.02
1996cb	IIb	Feb 13, 2001	1515	F555W	700	51953.18	23.61±0.07
1996cb	IIb	Apr 30, 2001	1591	F814W	700	52029.93	21.88±0.05
1996cb	IIb	May 13, 2001	1604	F814W	700	52042.65	21.95±0.04
1997bs	IIn	Mar 4, 2001	1417	F555W	700	51972.46	25.79±0.25
1997ef	Ic	Apr 28, 2001	1233	F814W	700	52027.50	20.00±0.03
1998S	IIn	Oct 1, 2000	940	F814W	700	51818.03	21.50±0.03
1998S	IIn	Mar 16, 2001	1106	F555W	700	51984.16	22.13±0.03
1999bw	IIn	Jan 9, 2001	626	F555W	700	51918.58	24.08±0.06
1999eb	IIn	Aug 16, 2000	332	F814W	700	51772.68	19.19±0.03
1999eb	IIn	Oct 11, 2000	387	F814W	700	51828.42	19.58±0.03
1999eb	IIn	Jan 6, 2001	475	F555W	700	51915.61	21.11±0.03
1999eb	IIn	Jul 9, 2001	659	F814W	700	52099.94	22.23±0.04
1999el	IIn	Oct 30, 2000	374	F814W	700	51847.74	20.04±0.03
1999el	IIn	Apr 25, 2001	551	F814W	700	52024.74	22.34±0.04
1999el	IIn	May 8, 2001	563	F555W	700	52037.13	22.68±0.03
1999gi	II-P	Jan 24, 2001	409	F555W	700	51933.43	19.94±0.02
1999gq	II	Jan 14, 2001	530	F814W	700	52074.24	22.07±0.05
2000P	IIn	Dec 6, 2000	245	F555W	700	51884.56	21.22±0.02
2000P	IIn	Apr 23, 2001	383	F814W	700	52022.60	21.33±0.03
2000cx	Ia	Jul 10, 2001	356	F675W	280	52100.07	21.97±0.06[f]
2000cx	Ia	Jul 10, 2001	356	F814W	280	52100.07	21.42±0.04[g]

[a]UT date of the observation.

[b]Approximate age of the SN in days since discovery.

[c]Exposure time in seconds.

[d]Modified Julian Date − 2,400,000.

[e]Magnitude in the WFPC2 system. An uncertainty of 0.02 mag is added in quadrature to the errors of the F555W and F814W observations, while 0.05 mag is added to the F675W error for SN 2000cx. These magnitudes are converted to Johnson V and Cousins I, except in the case of SN 2000cx.

[f]The transformed standard Johnson R magnitude is 22.10±0.06.

[g]The transformed standard Cousins I magnitude is 21.38±0.04.

Table 2. Late-time decline rate of several SNe IIn.

SN	Filter	Decline rate[a]	Age[b] (days)
1995N	V	0.18±0.01	1400 − 2200
1997bs	V	0.21±0.02	300 − 1400
1998S	V	0.34±0.03	300 − 1100
1995N	I	0.05±0.01	1900 − 2200
1998S	I	0.56±0.05	300 − 1000
1999eb	I	0.86±0.01	300 − 600
1999el	I	1.30±0.03	400 − 600

[a]Magnitude decline per 100 days.

[b]Approximate age of the SN when the decline rate is derived.